Faults Detection and Remote Monitoring System for Induction Motors using MCSA Technique

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***Abstract*-This paper introduces a methodology for faults detection in induction motors based on MCSA using the Fast Fourier Transform algorithm (FFT). A significant advantage of implementing this technique is that only the stator current measurement required.**

This work also describes the method for determining the exact amplitude of the harmonic fault, regardless of the sampling time used, thus making data acquisition and subsequent analysis easier. Experimental results show that the methodology is sensitive to several failures such as: broken rotor bar, bearing damage, rotor eccentricity and shorted turns.

Furthermore, a brief description of the design and implementation of a fully automated and remote monitoring system is included as well.

I. INTRODUCTION

In industrialized countries, induction motors are responsible for between 40% and 50% of energy consumption [1]. Recent studies indicate that 90% of the failures in machines occur due to miss function of the internal components, such as the main motor [1].

A wide range of techniques have been proposed for detecting faults in induction motors, extending from sensor-less methods, to injecting high frequency current into the stator coils [1][3][5].

Numerous methodologies for monitoring and diagnosing induction motors are based on analysing the frequency spectrum resulting from the fast Fourier transform algorithm (FFT). However, not many techniques where tested in industrial environments [6].

First of all, a brief description of the most important faults in induction motors is presented, in conjunction with a first classification of these. Secondly, the mathematical data acquisition model is introduced. Then, the diagnostic methodology is described. After that, laboratory and industrial tests are analyzed in order to validate the methodology. Finally, the design and implementation of a fully automated and remote monitoring system is described.

II. FAILURES IN INDUCTION MOTORS

Most of the failures in induction motors can be classified in two main groups: isolation and mechanical faults [7]. In [7], failures in asynchronous motors are briefly presented.

Isolation failures are commonly characterised by stator coils short-circuits.

Mechanical faults are commonly associated to rotor or rotor related damages. The most important mechanical failures are: broken rotor bars and rings, bearings damage, irregular gaps (static and dynamics rotor eccentricities), unbalances and refrigeration troubles.

In general, failures in electrical machines occur mainly in bearings and stator coils. The following are statistics focused on asynchronous motors with squirrel cage rotor. A pie chart is shown in Fig. 1 [2], [6].

Bearings fault related: 41%
Stator faults related: 37%
Rotor faults related: 10:
Other problems: 12%

III. DATA ACQUISITION MODEL

There are several techniques that can be used for detecting faults in induction motors. The MCSA (Motor Current Signal Analysis) is a non-invasive, on-line monitoring technique for diagnosing problems in induction motors. This method is based on the spectral decomposition of the steady state stator current which can be acquired with simple measurement equipment and under normal operation of the machine. MCSA can diagnose failures such as broken rotor bars, shorted turns, bearing damage and air gap eccentricity [12]. In the MCSA method, the current frequency spectrum is obtained and specific frequency components are analyzed. These frequencies are related to well-known machine faults. Therefore, after processing the stator current, it is possible to infer about the machine's condition [1], [2], [6].

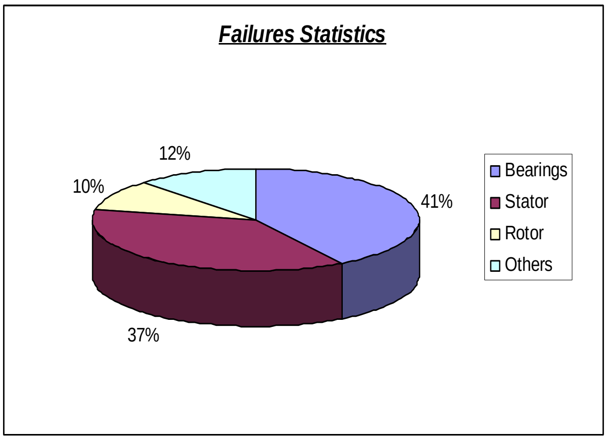

Fig. 1. Statistics related to failures in induction motors.

An accurate comprehension of the influence of each variable is desired for the correct interpretation of the data acquired. In this work the frequency spectrum is obtained using the FFT. For the cases where the data acquisition is done for a complete number of cycles of the frequency component being studied, obtaining its amplitude and frequency is relatively straightforward. However, this is rarely the case, leading to cases where certain frequency components mask others of interest. This is commonly known as leakage [11]. Another fact which must be taken into account is that the motor's load conditions are not always the same; this alters the fault signature characteristics as well. The main objective of the technique described in this paper, is to identify the frequency components associated with the types of failures previously mentioned, independently from the motors' operating conditions and data acquisition, and monitor them in order to determine the condition of the machine. To avoid the masking effect, the signal is multiplied by a function (also known as window) to reduce the discontinuity. Both the description of different windows and their results are not analyzed in this paper. Instead, it focuses on the acquisition of the current's frequency components' amplitudes, of those components which are induced by each failure.

When the number of samples is sufficiently high (tests have been done using sampling rates of 5 kHz, 2 kHz and 1 kHz during a sampling time of 8 s and 10 s), the values of the discrete Fourier series converge to those of the continuing Fourier series.

Taking a signal $f(t) = \beta sin(wt + \theta)$ and $x = wt$, then $f(x) = \beta\sin(x + \theta)$. If $k + y$ periods are sampled, with k an integer and y real, the expression for the *k-th* frequency component (with sufficient number of samples) is

$$a_k = \frac{1}{2\pi k + 2\pi y} \int_0^{2\pi k+2\pi y} \beta\sin(x + \theta) e^{-\frac{2\pi k}{2\pi k+2\pi y} x j} dx. \quad (1)$$

Solving (1), the real part of a_k is

$$\beta \begin{bmatrix} -\frac{\cos(2\pi y + \theta + 4k\pi)}{4\pi(y + 2k)} - \frac{\cos(2\pi y + \theta)}{4\pi y} \\ -\frac{\cos(\theta)\, k}{4\pi(y + k)(y + 2k)} + \frac{\cos(\theta)\,(2y + k)}{4\pi y(y + k)} \end{bmatrix} \quad (2)$$

and the imaginary part of a_k is

$$\beta \begin{bmatrix} \frac{sin(2\pi y + \theta + 4k\pi)}{4\pi(y + 2k)} - \frac{\sin(2\pi y + \theta)}{4\pi y} \\ + \frac{\sin(\theta)\, k}{4\pi(y + k)} + \frac{\sin(\theta)\, k}{4\pi y(y + k)} \end{bmatrix}. \quad (3)$$

From (2) and (3), the modulus of a_k is

$$\frac{\beta}{4\pi} \begin{bmatrix} 2(y\,((\mathrm{y} + 2\mathrm{k})\cos(2\pi y + \theta) \\ -2\cos(\theta)\,(y + k))\cos(2\pi y + \theta + 4k\pi) \\ -y\big((y + 2k)\sin(2ky + \theta) - 2\sin(\theta)\,k\big) \\ \sin(2\pi y + \theta + 4\pi k) \\ -2\cos(\theta)\,(y^2 + 3ky + 2k^2)\cos(2\pi y + \theta) \\ -2\sin(\theta)\,k(y + 2k)\sin(2\pi y + \theta) \\ +(2\cos(\theta) + 1)y^2 \\ +2(2cos^2(\theta) + 1)ky + 4k^2) \end{bmatrix}^{\frac{1}{2}} \left|\frac{1}{y(y+2k)}\right| \quad (4)$$

Then, the limit of $|a_k|$ as k tends to infinity:

$$\lim_{\substack{k\to\infty \\ (k \,\epsilon\, N)}} |a_k| = \beta \left|\frac{1}{y}\right| \begin{bmatrix} -2(\cos(\theta)\cos(2\pi + \theta) \\ + \sin(\theta)\sin(2\pi y + \theta) - 1) \end{bmatrix}^{\frac{1}{2}}$$

$$= \beta \left|\frac{\sin(\pi y)}{2\pi y}\right|. \quad (5)$$

Substituting πy for Ω into (5)

$$\lim_{\substack{k\to\infty \\ (k \,\epsilon\, N)}} 2|a_k| = \beta \left|\frac{\sin(\Omega)}{\Omega}\right|,$$

where the period is equal to (6)

$$T = 2\pi k + 2\Omega$$

Based on (6), when a complete number of cycles are sampled($\Omega = 0,\ \mathrm{y} = 0$), the following is obtained:

$$\beta = 2|a_k|. \quad (7)$$

For nearly all frequency components, the value of y will be different from zero. Thus, the following method must be applied to obtain the real magnitude of the *k-th* component [13].

Consider a_k as the main component of the first harmonic:
If $0 < y < 0.5$ the second component of the first harmonic will be a_{k+1}.
If $-0.5 < y < 0$ the second component of the first harmonic will be a_{k-1}.

Then, the ratio between the main and the second component of the first harmonic is called Ψ.

$$\Psi = \frac{|a_k|}{|a_{k\pm1}|} \quad (8)$$

Equations (6) and (8) yield

$$\Psi = \frac{\frac{\sin(\pi|y|)}{2\pi|y|}}{\frac{\sin(\pi(|y| \pm 1))}{2\pi(|y| \pm 1)}} = \frac{(1 \pm |y|)}{|y|} \quad (9)$$

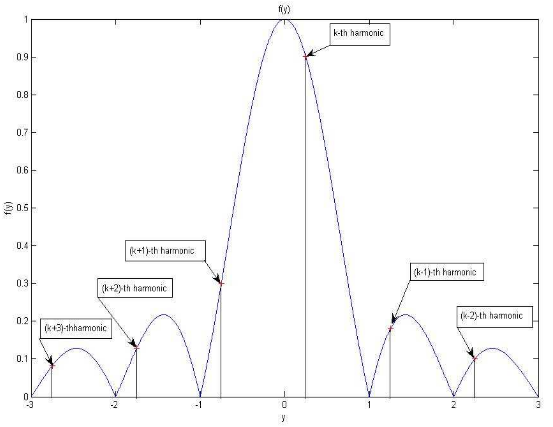

Fig. 2. Relationship between main and secondary harmonics when the number of samples is sufficiently large.

Equation (9) gives an expression for y(Ψ).

$$|y| = \frac{1}{\Psi + 1} \tag{10}$$

Equation (6) with a number of samples sufficiently high yields

$$2|a_k| = \beta \frac{|\sin(\pi y)|}{|\pi y|}. \tag{11}$$

Finally, the equation for the real magnitude of the first harmonic is deduced from (10) and (11),

$$\beta = \frac{|a_k| 2\pi}{\sin\left(\frac{\pi}{\Psi + 1}\right)(\Psi + 1)}. \tag{12}$$

Equation (12) is used to calculate the exact amplitude of a given fault's signal. Likewise, for deducing the exact frequency of the defect, the next equation is used,

$$f = \frac{k \pm \frac{1}{\Psi + 1}}{t_s}, \tag{13}$$

where t_s is the complete sample's length in seconds.

Therefore, from (12) and (13), it is possible to deduce both the exact amplitude and frequency for any defect's signal.

Fig 2. shows the relationship between the main and second harmonics when the number of samples is sufficiently large.

IV. MONITORING AND DIAGNOSIS METHODOLOGY

A. *Frequencies Induced by each Fault*

The frequencies of the signals induced by each fault (broken bars, shorted turns, eccentricity and bearings failure), are calculated as a function of some of the motor's characteristic data and operating conditions (these functions are extensively detailed in the existing bibliography).

1. *Broken bars [1][8]:*

$$f_b = f_1(1 \pm 2s), \tag{14}$$

where f_1 is the electrical supply frequency and s is the per-unit slip.

2. *Shorted Turns [6] :*

$$f_{st} = f_1\left\{\frac{n}{p}(1 - s) \pm k\right\}, \tag{15}$$

where f_1 is the electrical supply frequency, n is a positive integer number (1, 2, 3…), s is the per-unit slip and k can be equal to 1, 3, 5 or 7.

3. *Eccentricities [2]:*

$$f_{ec} = f_1\left[(r \pm n_d)\left(\frac{1 - s}{p}\right) \pm n_{ws}\right], \tag{16}$$

where f_1 is the electrical supply frequency, r is the number of slots, n_d is equal to ± 1, p is the number of pole pairs, s is the per-unit slip and $\mathrm{n_{ws}}$ can be equal to 1, 3, 5 or 7.

Reference [10] provides a simplified version of (16).

$$\mathrm{f_{ec}} = \mathrm{f_1} \pm k\mathrm{f_{rm}} \tag{17}$$

where f_1 is the electrical supply frequency, k is equal to an integer number and f_{rm} is the rotor's mechanical frequency.

4. *Bearing failures [9][10]:*

$$\begin{aligned} f_0 &= 0.4 \times n \times f_{rm} \\ f_1 &= 0.6 \times n \times f_{rm}, \end{aligned} \tag{18}$$

where f_0 and f_1 are respectively the lower and upper frequencies, n is the number of balls in the bearings and f_{rm} is the rotor's mechanical frequency.

As it was shown, given a motor's characteristic data, its current's samples and the value of the slip, it is possible to determine all the frequencies of the signals induced by each fault.

B. *Diagnostics*

It is necessary to stress the fact that during data acquisition, the result of applying the FFT to the stator current is normalized as a function of the first harmonic amplitude. This way, the amplitudes of the components induced by each fault are independent from the motor's load conditions.

The stator current must be sampled periodically, and each time, the real values of the faults' amplitudes and frequencies must be determined using (12) and (13). Finally, the new amplitudes must be compared to the previous ones in order to detect whether a fault is evolving or the motor's conditions are normal.

V. LABORATORY TEST RESULTS

In this section, laboratory tests results for all: broken rotor bars, shorted turns, rotor's eccentricity and bearing failure are presented. Amplitudes shown in this section are calculated using (12).

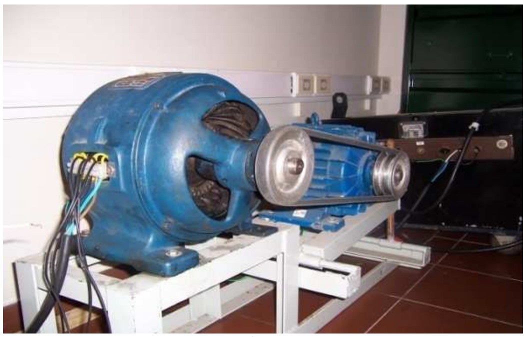

Fig. 3. View of the work bench.

1. Broken bars

The frequencies were determined using (14).

$$s = 0.0473 \quad (1429rpm)$$
$$f_{b-} = 45.25\ Hz$$
$$f_{b+} = 54.75\ Hz$$

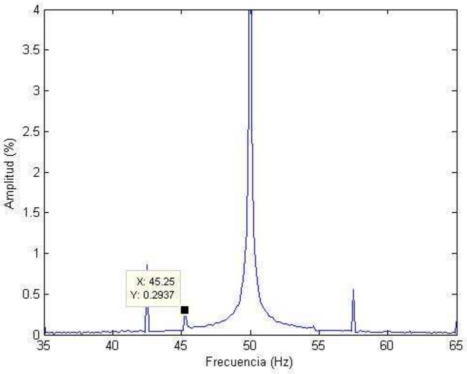

Fig. 4. FFT of the initial condition for broken bars.

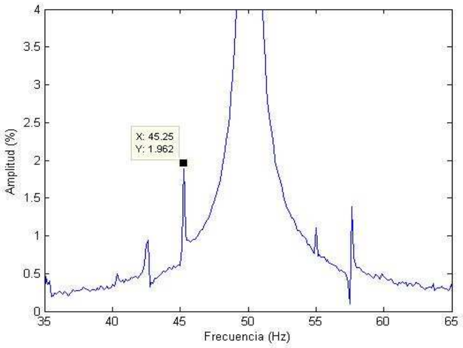

Fig. 5. FFT with 3 broken bars.

TABLE I
RESULTS OF BROKEN BARS

Frec (Hz)	Amp (%)	Nr Broken Bars
45.25	0.2937	0
45.25	1.028	1
45.25	1.83	2
45.25	1.962	3

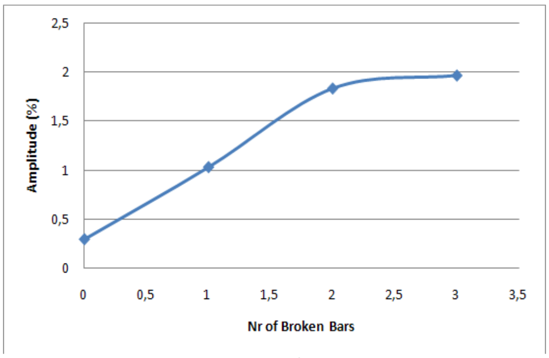

Fig. 6. Broken bars fault evolution.

Fig. 6 shows how the amplitude of one of the frequency components associated with broken bars, increase as a function of the number of bars that have broken.

2. Shorted Turns

The frequencies were determined using (15) with $n = 3$ and $k = 1$.

$$s = 0.0153 \quad (1477rpm)$$
$$f_{\mathrm{st}} = 23.85\ Hz\ (n = 3 \text{ and } k = 1)$$

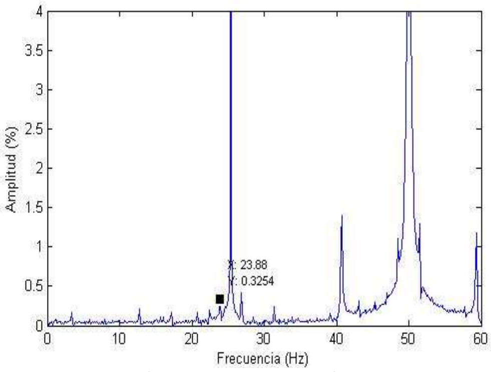

Fig. 7. FFT of the initial condition for short-circuits.

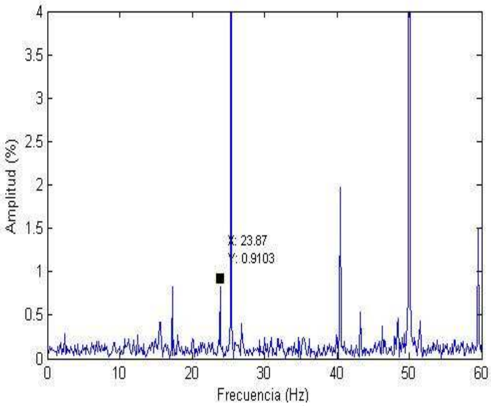

Fig. 8. FFT with 1.95% of short-circuits

TABLE II
RESULTS OF SHORT-CIRCUITS

Frec (Hz)	Amp (%)	SC (%)
23.85	0.8	0
23.85	1.34	1.02
23.85	1.47	1.39
23.85	1.89	1.95

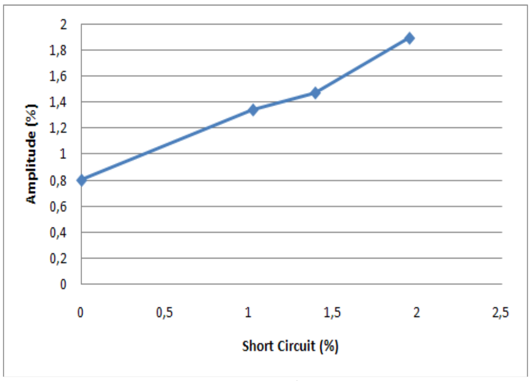

Fig. 9. Shorted turns fault evolution.

3. *Rotor's Eccentricity*

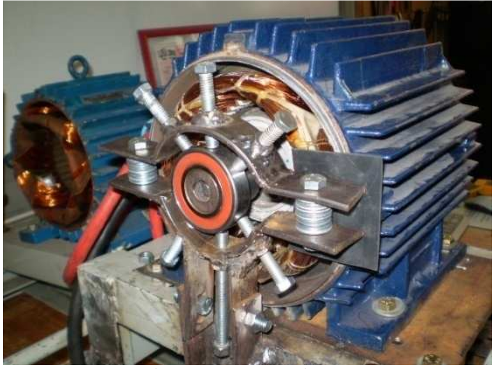

Fig. 9. View of the eccentricity fault's work bench.

For quantifying the rotor's eccentricity on each test, first the difference between the positions of the rotor and stator's geometrical centres is measured, and is then divided by the maximum possible radial displacement (g).

$$e(\%) = \frac{\sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}}{g} \qquad (19)$$

where x_0, x_i, y_0, y_i and g are shown in Fig. 10.

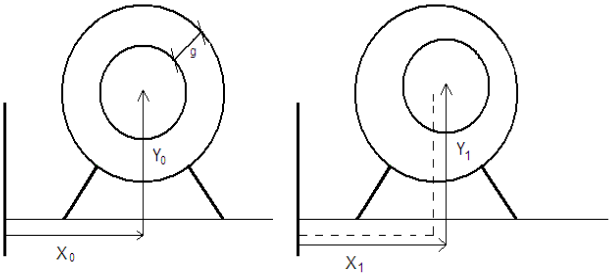

Fig. 10. Eccentricity measurements.

As the rotor's eccentricity is changed, its rotational speed varies. Hence, the values of the frequency components, associated with this fault, are affected. These frequencies were determined using (17) with $k = -1$.

$$s = 0.071\ (1393rpm)$$
$$f_{ecc} = 26.78\ Hz$$

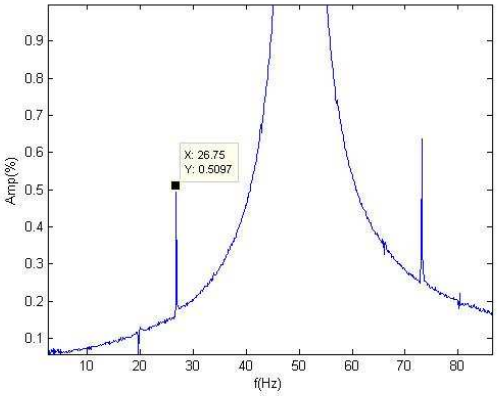

Fig. 11. FFT of the initial condition for rotor's eccentricity.

$$s = 0.071\ (1361rpm)$$
$$f_{ecc} = 27.31\ Hz$$

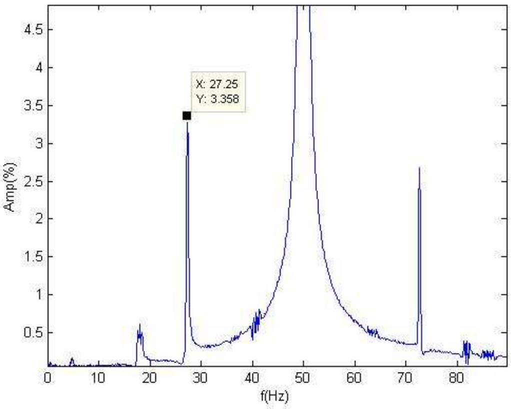

Fig. 12. FFT with 87.3% of eccentricity.

TABLE III
RESULTS OF ECCENTRICITY

Ecc (%)	Amp (%)
0	0.59
44,5	1.96
87,3	4.94

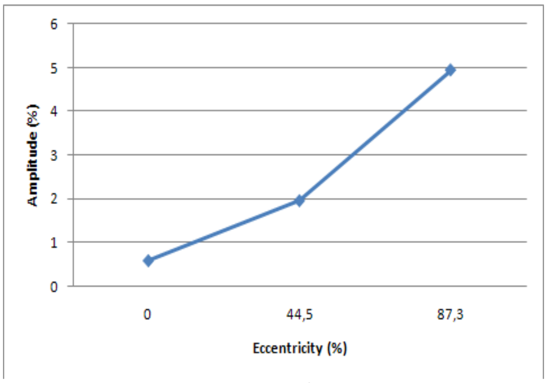

Fig. 13. Shorted turns fault evolution.

4. Bearing Damage

The frequencies were determined using (18).

$$s = 0.012\ (1482rpm)$$
$$f_0 = 69.16\ Hz$$

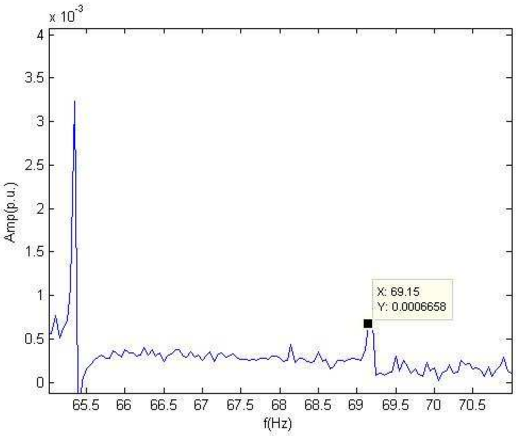

Fig. 14. FFT without bearing damage.

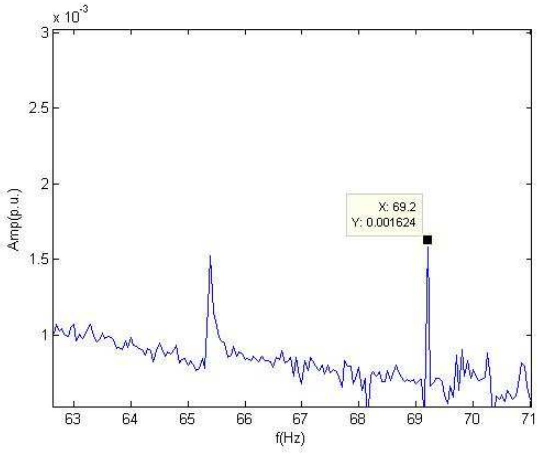

Fig. 15. FFT with bearing damages.

TABLE IV
RESULTS OF BEARING DAMAGES

Bearing Balls	Amp (%)
0	0.105
1	0.110
2	0.160
4	0.185

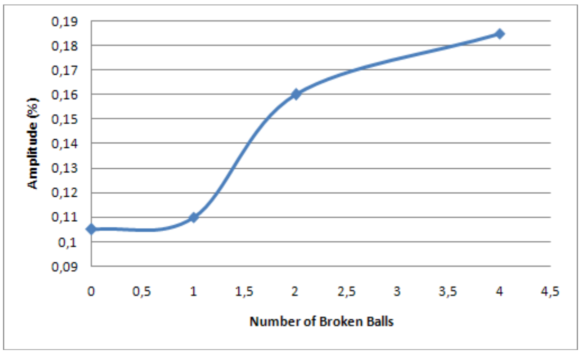

Fig. 16. Bearing damages evolution.

VI. INDUSTRIAL APPLICATION AND TESTS RESULTS

In this section, the design, implementation and tests results of a fully automated system which applies the technique shown above, is briefly described.

As it was mentioned in the previous sections, to diagnose any given motor, the only values required by this methodology are: the motor's characteristic data, rotational speed and a sample of its electrical current consumption. This is the reason why a fully automated system can be implemented. In fact, a methodology has been recently developed for determining the motor's rotational speed, using only its characteristic data and the electrical current's samples.

The system was designed to automatically monitor and diagnose faults in induction motors both remotely and in real-time. Additionally, it has a web server for users to access the diagnostics of their motors. Moreover, the system triggers different types of alarms whenever a fault is detected and can even turn a motor off in case of a short-circuit detection.

Fig. 17 shows a general view of the system. All data is transmitted using the internet. Hence, the system can be used to diagnose faults in motors all around the world.

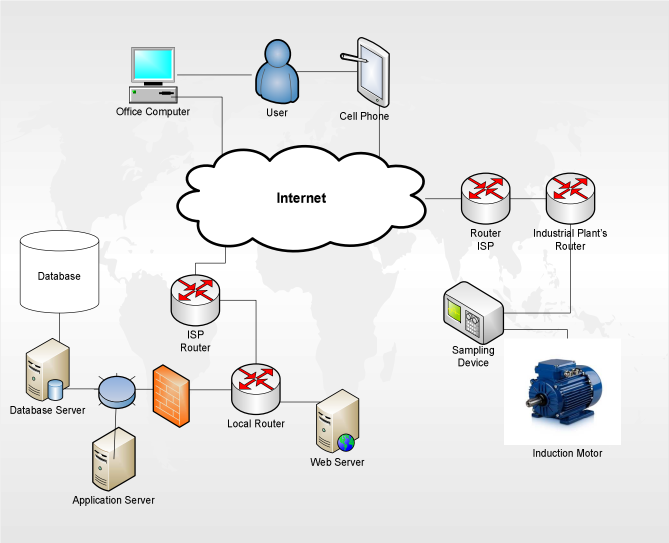

Fig. 17. General View of the System.

For achieving the goals of this paper, a design and construction of a device, which could both sample the current consumption and transmit the data to the application server was required. This sampling device was developed using a *RabbitCore* core module (RCM4000) and different current probes. The sampling device continuously executes two routines. The first one periodically samples the motor's electrical current and stores the data in local secondary memory, while the second one runs an FTP server. The device samples at 1000 kHz during 10 seconds (10000 samples). These specifications were chosen in order to store the least amount of samples possible, without losing the frequency resolution required.

At the same time, the application server (implemented with

JAVA programming language) continuously downloads the data from all the sampling devices and applies the methodology described in the previous sections.

Each time the values of every fault's frequency components are obtained, the application server retrieves the reference values from the system's database and compares them in order to determine the conditions of the motor.

Finally, the web server allows users to access the diagnostics of the motors' conditions. Furthermore, it allows system administrators to add new industrial plants, businesses, motors and users to the database.

Both laboratory and industrial tests results were satisfactory. Fig. 18 shows the prototype of the sampling device used for laboratory tests.

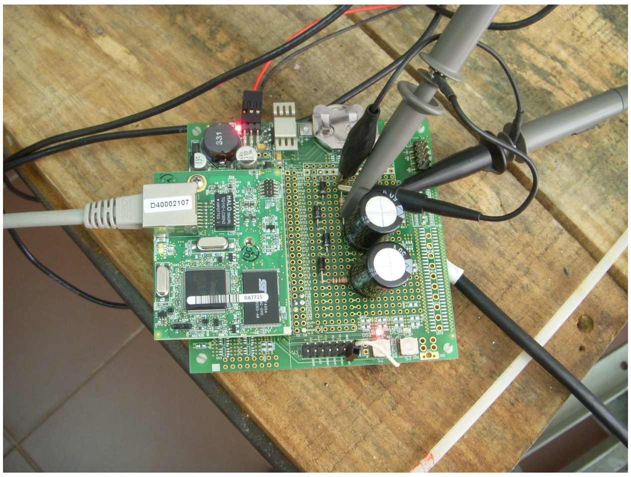

Fig. 18. Prototype of the Sampling Device.

VII. SUMMARY AND CONCLUSIONS

0In this paper, a methodology based on MCSA is presented for monitoring and diagnosing faults in induction motors. This method is able to ascertain the exact value of both magnitude and frequency of the signal's components, regardless of the sampling time. Therefore, studies of the faults' growth tendencies are easier.

Laboratory tests results for broken rotor bars, shorted turns, rotor's eccentricity and bearing faults are shown. The tests verified all failures' studies. The results show that with this technique, it is possible to detect faults in an incipient stage.

Finally, the design and implementation of the fully automation of this method is briefly described. Both laboratory and industrial test showed satisfactory results.

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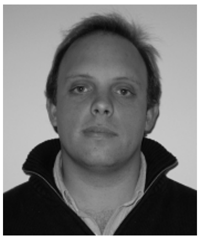
IX. BIOGRAPHIES

José Ignacio Terra was born in Montevideo, Uruguay on September 30, 1986. He received the degree of Telematics Engineer from the University of Montevideo in 2010, and now he is currently working in the electrical motors research group in the research institute (CITEM) of the University of Montevideo.



Marcelo Castelli (M'2006) was born in Montevideo, Uruguay on February 4 1979. He received the degree of Engineer from the University of Montevideo in 2004, and the PhD degree from the University of Navarra (Spain) in 2010, in the field of electrical machines.

After two years of research in TECNUN (Technological Campus of the University of Navarra), form 2004 to 2006, he came back to Uruguay to work in the research institute (CITEM) of the University of Montevideo. He is currently involved in the development of predictive maintenances systems, and energy savings control systems. Also, he was the Uruguayan PES Chapter Chair between 2007 and 2009 and currently he is the Uruguayan PES Vice-Chapter Chair.

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